Project 029(A) National Jet Fuel Combustion Program – Area #5: Atomization Test and Models

Purdue University

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University Participants

Purdue University
- PI(s): Robert P. Lucht, Jay P. Gore, Paul E. Sojka, and Scott E. Meyer
- FAA Award Number: COE-2014-29A, 401321
- Period of Performance: October 1, 2018 to September 30, 2019
- Tasks:
  1. Obtain phase Doppler anemometry (PDA) data across one plane in the variable ambient pressure spray (VAPS) test rig operated with the referee rig nozzle for numerous fuels under near-lean blowout (LBO) conditions and under cold fuel/cold air flow conditions approximating ground light-off (GLO) and high-altitude relight (HAR) conditions
  2. Extend PDA measurements to obtain data across multiple planes for an evaluation of detailed combustor simulations by Suresh Menon, Vaidya Sankaran, and Matthias Ihme
  3. Obtain PDA and/or Malvern measurements for selected operating conditions in the VAPS test rig to provide data for the spray correlation analysis of Nader Rizk
  4. Perform PDA measurements for fuel blends, including Fuel X and/or another blend designed for testing differences in atomization characteristics, to examine the sensitivity of correlations and computations to changes in fuel properties
  5. Ensure data quality through repeated tests at Purdue and through comparisons of spray measurements at Pratt and Whitney, the University of Dayton Research Institute/Air Force Research Laboratory, and the University of Illinois at Urbana/Champaign.

Project Funding Level
The funding level from the FAA was $120,000 for year 5. Purdue University provided cost-sharing funds in the amount of $120,000.

Investigation Team
- PI Dr. Robert Lucht, Bailey Distinguished Professor of Mechanical Engineering is responsible for overseeing the project at Purdue University. He is also responsible for mentoring one of the graduate students, coordinating activities with Stanford, working with all parties for appropriate results, and reporting results as required.
- Co-PI Dr. Jay Gore, Reilly Professor of Mechanical Engineering works closely with the PI and oversees the work performed by one of the graduate students. He is also responsible for interacting with the CFD groups to suggest comparisons with experiments and with results of an adaptive grid solver.
- Co-PI Dr. Paul Sojka, Professor of Mechanical Engineering is mentoring one of the graduate students and is responsible for supervising the spray measurements.
• Co-PI Scott Meyer, Managing Director of Maurice J. Zucrow Laboratories is responsible for coordinating facility upgrades and for performing facility design reviews.
• Graduate student Daniel Shin is responsible for performing the PDA measurements and for modifying the VAPS test rig for operation under near-LBO and cold start conditions. Graduate student Hasti Veeraraghava Raju has conducted simulations with an adaptive grid solver and has performed comparisons with experimental results and results from the other CFD groups. Graduate student Neil Rodrigues contributes to the project by providing advice for the PDA measurements and technical editing.

Project Overview
The objectives of this task, as stated in the Invitation for ASCENT COE Notice of Intent (COE-2014-29), are to “measure the spray characteristics of the nozzles used in the Referee Combustor used in Area 6 tests and to develop models for characterizing the atomization and vaporization of the reference fuels.” We are conducting experiments within the joint experimental and modeling effort. The experimental tasks are being performed at Purdue University, and the modeling tasks are being performed by Prof. Matthias Ihme’s group at Stanford University, Prof. Suresh Menon’s group at Georgia Tech, and Vaidya Sankaran’s group at United Technologies Research Center (UTRC). Nader Rizk is developing spray correlations based on the measurements.

Purdue University has highly capable test facilities for measuring spray characteristics over wide ranges of pressure, air temperature, and fuel temperature. The experimental diagnostics applied in this project include PDA and high-frame-rate shadowgraphy. The atomization and spray dynamics for multiple reference and candidate alternative fuels have been characterized for the referee rig nozzle operating under near-LBO conditions. In the future, measurements will be performed for these fuels under operating conditions characteristic of HAR. A new fuel, IH2 (Shell CPK-0), has been added to the test matrix and is being investigated under LBO and cold start conditions.

Task 1 - Measurement of Spray Characteristics under Near-Lean-Blowout and Chilled Fuel Conditions
Purdue University

Objective(s)
The objectives of this task are to visualize and measure the characteristics, including drop size distributions and axial velocity components, of sprays generated by a nozzle in the referee combustor in the Area 6 tests. The resulting data are being applied by Nader Rizk to develop spray correlations and by Matthias Ihme (Stanford University), Suresh Menon (Georgia Tech), and Vaidya Sankaran (UTRC) to develop a submodel for detailed computer simulations. The spray data are being shared with the FAA National Jet Fuel Characterization Program (FAA-NJFCP) team members for their interpretation and for the development of modeling, simulation, and engineering correlation-based tools.

An upgraded VAPS test rig at Purdue University is utilized to measure spray characteristics over a range of pressures, atomizing gas temperatures, and fuel temperatures. Our work has led to the identification of challenges associated with performing reliable and reproducible spray measurements while keeping the windows of the apparatus clean. PDA has emerged as the technique of choice for obtaining drop size distribution and axial and radial velocity data for comparison with numerical simulations. The VAPS facility was upgraded to support experiments over the entire range of fuel and air temperatures and pressures of interest. We have compared reacting and nonreacting spray data by collaborating with the UIUC/UDRI/AFRL Area 6 team.

The experimental data have supported the continued development and evaluation of engineering spray correlations, including the dependence of the Sauter mean diameter, spray cone angle, and particle number density per unit volume on the fuel properties at the fuel and air temperatures of interest. The experimental data provide detailed statistical measurements for comparison with high-fidelity numerical simulations of mixing and combustion processes. The predicted spatial distribution of the liquid fuel and of the resulting vapor and breakdown components from the liquid fuels critically affects the ignition, flame stabilization, and pollutant formation processes.
The project objectives are summarized as follows:

1. Obtain PDA data across different planes in the VAPS test rig operating with the referee rig nozzle for numerous fuels under near-LBO conditions and under cold fuel/cold air flow conditions approximating GLO and HAR conditions
2. Provide data to the research groups of Suresh Menon, Vaidya Sankaran, Matthias Ihme, and Jay Gore for simulations
3. Conduct PDA measurements for selected operating conditions in the VAPS test rig to provide data for the spray correlation analysis of Nader Rizk
4. Perform PDA measurements for fuel blends, including Fuel X and/or another blend designed for testing differences in atomization characteristics, to examine the sensitivity of correlations and computations to changes in fuel properties
5. Ensure data quality through repeated tests at Purdue and through comparisons with spray measurements at P&W, UDRI/AFRL, and UIUC

Research Approach
The Purdue University VAPS test rig facility is designed to measure spray characteristics over wide ranges of pressure, atomizing gas temperature, and fuel temperature. Liquid fuels can be supplied to the test rigs by multiple systems. A facility-integrated system draws fuel from one of two certified flame-shield fuel containments to test standard aviation fuels as well as alternative blends. A mobile fuel system, developed under the combustion rules and tools (CRATCAF) program and redeployed during the first year of the NJFCP program, is being utilized for further control of additional injector circuits and for supplying alternative fuel blends. Both systems were designed with two independently controlled and metered circuits to supply fuel to the pilot and main injector channels of the test injector. The mass flow rates of both fuel supplies are measured with Micro Motion Elite® Coriolis flow meters. A nitrogen sparge and blanket ullage system is used to reduce the dissolved oxygen content of the fuel, which is monitored by a sensor immediately upstream of the fuel control circuits. High-pressure gear pumps provide fuel at rates of up to 30 kg/hr, which is supplied to the control circuits at a regulated line pressure of 10 MPa. The mobile fuel system was built with two onboard heat exchangers, and a chilling unit controls the fuel temperature over a range of 193–263 K (-80 ºC to -10 ºC).

Milestone(s)
The tasks performed in FY2019 are listed below:

Quarter 1
1. The VAPS test rig and PDA system were moved to the new High-Pressure Combustion Laboratory.
2. A new stand for the VAPS test rig was designed and fabricated.
3. A new exhaust pipe line for the VAPS test rig was designed for installation in the new test cell.
4. Modifications and insulation were applied to the major facility nitrogen lines for the pressure vessel and airbox flows.
5. The expansion of the data acquisition and control system (DACS) in the new test cell was initiated.
6. The chapter on spray measurements for the American Institute of Aeronautics and Astronautics (AIAA) NJFCP book was edited and revised.
8. Fuel sensitivity in LBO trends was successfully demonstrated with a flamelet-based combustion model, and the computational time was reduced by 60% compared with detailed chemistry simulations.
9. “LBO simulations and flame structure analysis with detailed chemistry and FGM model” was presented orally at the NJFCP review meeting in Cleveland, Ohio.
10. The need for detailed flow and combustion measurements was identified for computational model evaluations and was discussed in detail at the NJFCP review meeting.

Quarter 2
1. Modifications and improvements of the DACS for the VAPS test rig in the new test cell were completed.
2. The chapter on spray measurements for the AIAA NJFCP book was edited and revised.
3. Manuscripts describing the results of LBO and cold start measurements were prepared for submission to the AIAA Journal of Propulsion and Power and the AIAA Journal, respectively.
4. Domain sensitivity analyses were initiated in CFD calculations.
5. Further detailed analysis of the flame structure were performed using the flamelet-generated manifold (FGM) combustion model.
Quarter 3
1. A new design for vessel window port orientation (90-degree angle between windows) was proposed for planar laser-induced florescence (PLIF), structured laser illumination planar imaging (SLIPI), and PIV imaging measurements.
2. A manuscript on LBO measurements was submitted to the AIAA Journal of Propulsion and Power.
3. The chapter on spray measurements for the AIAA NJFCP book was edited and revised.
4. A CFD model for simulating the actual size of the test rig plenum was developed.
5. The finite-rate chemistry (FRC) model employed for LBO simulations was validated using CARS measurements for temperature and species and using PIV measurements for velocity in a laboratory turbulent jet flame.
6. A manuscript was prepared and submitted to the Journal of the Energy Institute on FRC model validation.
7. Chemical pathway analyses were initiated for flames under turbulent conditions.

Quarter 4
1. A new vessel window design was implemented to enable PLIF, SLIPI, and PIV measurements of the spray structure and dynamics.
2. A manuscript for LBO measurement was accepted by the AIAA Journal of Propulsion and Power and is currently in press.
3. A manuscript on the cold start measurements was prepared for submission to the AIAA Journal.
4. The AIAA book chapter was revised.
5. LES simulations were performed for the domain sensitivity.
6. The manuscript on FRC simulations was revised based on feedback from the reviewers, and a revised version was then submitted to the Journal of the Energy Institute.
7. A methodology for constructing quantitative reaction pathways was established to study the chemical pathways under turbulent conditions using the atmospheric jet flame LES results.

Major Accomplishments
Experimental contributions
The work described in this section is part of the Purdue contribution to a larger FAA-funded effort, NJFCP. The major objective of the work at Purdue was to measure spray properties (droplet size, droplet velocity, spray cone angle) for a variety of jet fuels and candidate jet fuels under a wide range of conditions, including LBO and GLO conditions. These measurements were successfully performed last year using PDA, which provided single-point measurements of the spray. For a more detailed investigation of the spray using two-dimensional (2D) planar imaging, PLIF and SLIPI were proposed, which required a significant modification of the test rig. The remainder of this section presents the process of the test rig modification for the new High-Pressure Combustion Laboratory test cell at Purdue.

Experimental systems
The Purdue VAPS test rig comprises two major components: the airbox assembly and the pressure vessel. The airbox assembly is a length of pipe in which the hybrid air-blast pressure-swirl atomizer is mounted. The airbox is placed within the pressure vessel, which allows a pressurized atomizing gaseous flow through the airbox to be isolated from the vessel to create a pressure difference across the gas swirl. The pressure vessel is rated to withstand 4.14 MPa (600 psi) at 650 °C (1200 °F). The vessel originally had four windows in a single horizontal plane, which allowed laser diagnostic measurements to be performed within the test section. Figure 1 shows schematic diagrams of the previous window system and the new window system. The original window system included two diametrically opposed 114-mm window ports and two 64-mm window ports at a 60° angle with respect to one of the 114-mm ports. This window system was modified to include three 114-mm window ports, with one port oriented at a 90° angle with respect to the diametrically opposed 114-mm window ports, and one of the 63.5-mm window ports was removed. This new window system allows PLIF and SLIPI measurements, which can provide a 2D representation of the spray rather than the point measurements produced by PDA.

A mobile fuel system was used to supply pressurized fuel to the injector mounted on the airbox. The mobile fuel system had a chiller unit with two heat exchangers to chill the fuel to the desired temperature. This mobile fuel system was redesigned and integrated with the new stand for the VAPS test rig, as shown in Figure 2. The fuel control and supply system panels were reproduced from the mobile fuel system and were integrated into the VAPS test rig stand. Additionally, the chiller unit and two heat exchangers were removed from the test cell and reinstalled outside the test cell.
Figure 3 shows a photograph of the integrated VAPS test rig. The window purge manifolds are attached, and the flow lines for the airbox and vessel nitrogen flows are connected to the VAPS rig. The DACS box is also attached to the stand for measurement sensors, such as pressure transducers and thermocouples.

Figure 1. Schematic diagrams of the previous and modified window systems in the variable ambient pressure spray (VAPS) test rig.

Figure 2. Photographs of the modified fuel supply system integrated into the variable ambient pressure spray (VAPS) test rig stand.
Figure 3. Photograph of the variable ambient pressure spray (VAPS) test rig.

Proposed PLIF and PDA configuration

PLIF was proposed to provide 2D spray visualization and more qualitative measurements of the liquid volume distribution. PLIF is a powerful measurement technique and is widely used in spray and combustion applications requiring knowledge of the liquid and vapor phase concentrations and 2D representations of the flame and spray. In PLIF, a laser sheet illuminates the flow and excites the ground-state fluid molecules to a higher electronic energy state. The excited molecules then de-excite and emit light at a longer wavelength. A tracer species, such as a fluorescent dye, may be added to the fluid or may naturally be present in the fuel, such as aromatic hydrocarbon in fuels. The population of tracer species in a unit volume of the fluid is directly proportional to the fluorescence signal, which allows us to measure the concentration or mass distribution of the spray. The spray cone angle can also be measured from the 2D spray image. Time-resolved imaging of the spray measurement is possible with high laser pulse rates (10 kHz or higher), which enables an investigation of the time dependence of the spray regime characteristics. Figure 4 shows the proposed PLIF and PDA systems installed near the VAPS test rig. Each measurement will be performed separately under LBO conditions for the A2 fuel.
Computational contributions
The following section describes the computational efforts in predicting the fuel sensitivity of LBO in the referee combustor. The CFD model developed for LBO calculations is illustrated in Figure 5. The flow through all passages, including minute effusion holes on the liners, is resolved in this CFD model. The computational grid for flow simulations with all passages open is shown in Figure 6. The grid is locally refined in the regions with the steepest gradients and is relatively coarse in sections with weaker gradients, based on adaptive mesh refinement (AMR).

Reacting LES simulations were performed for the referee combustor using the finite volume-based compressible CFD solver CONVERGE (Convergent Science Inc., 2017). The gas-phase equations are described with a Eulerian approach, and the liquid spray is modeled with discrete injections of droplets using a Lagrangian approach. The subgrid stress tensor terms in the momentum equations are modeled using a non-viscosity-based one-equation model to obtain closure (Pomraning & Rutland, C.J., 2002). The combustion process is modeled using the FGM method, which has been successfully employed to predict phenomena such as flame extinction and reignition in spray flames (El-Asrag et al., 2016; Elasrag & Li, 2018; Ihme et al., 2005; Ihme & Pitsch, 2008; Ma et al., 2019; van Oijen et al., 2016). A compact kinetic mechanism based on fuel surrogates is used to represent chemical reactions (Hasti et al., 2018). The FGM model accounts for the effects of turbulence on the reaction rates via a joint PDF of the mixture fraction, the mixture fraction variance, and a reaction progress variable. A fully automated on-the-fly meshing strategy combined with the cut-cell Cartesian method and AMR was employed, and the mesh parameters were selected based on a previous grid sensitivity study (Hasti et al., 2018). Additional mesh evaluation studies for the present reacting flow conditions demonstrated that more than 90% of the turbulent kinetic energy is resolved. Additional details on the boundary conditions and the spray can be found in reports by Hasti et al. (2018; 2018).
The spray is represented by an ensemble of six ring injectors, each with prescribed cumulative distribution functions for the droplet diameter, average velocity, cone angle, mass flow rate, and parcel number. The spray boundary conditions (droplet diameter, average velocity, and cone angle) at 2 mm from the nozzle exit are obtained from the PDA measurements (see measurement details in our experimental contribution section) at 25.4 mm from the deflector plate (Bokhart et al., 2017; Bokhart et al., 2018). An ensemble of six ring injectors, each with its own droplet size and velocity distribution, represents the nozzle. Taylor analogy secondary breakup and dynamic drag models are employed to estimate the secondary breakup and resulting spray droplet dynamics. A droplet dispersion model is used to include the effects of the sub-grid-scale flow field on the discrete parcels. The droplet evaporation rates are calculated using the Frossling correlation based on the laminar mass diffusivity of the fuel vapor, mass transfer number, and Sherwood number. The prescribed fuel properties are set as those determined for the A2 and C1 fuels.
LES simulations were performed for a global equivalence ratio of 0.096, which was experimentally found to produce stable combustion. From this condition, the fuel flow rate is reduced in a gradual stepwise manner; larger time steps are initially applied, and the flow rate steps are progressively reduced as impending blowout behavior is observed, as shown in Figure 7. The simulations are run with a fixed global equivalence ratio for at least two flow-through durations, estimated as approximately 30 ms. The fixed equivalence ratio is maintained beyond 30 ms if a quasisteady heat release rate is not reached within either of those limits. The heat release rate is used as a criterion for identifying the LBO. The global equivalence ratio steps resulting from this process are plotted in Figure 7 as a function of time for fuel A2 (left) and C1 (right). The experimental data shown by red filled circles indicate that the C1 fuel (right) blows out at a higher equivalence ratio than the A1 fuel (left).

Reacting spray comparison under near-LBO conditions
Spray statistics were collected via LES calculations at a stable operating point over a period of two flow-through durations. The averaging process over two flow-through durations is started after the flame and heat release rate reach a quasisteady state. Figure 8 shows the experimental (Mayhew et al., 2017) and predicted droplet statistics as a function of radial distance for the FRC and FGM combustion models at four axial stations. The fuel spray exhibits a pattern, with smaller-diameter droplets near the hollow cone surface 10 mm downstream of the nozzle exit. This distribution widens in the radial direction toward the downstream locations, with larger droplets towards the center and smaller droplets in the outer regions. The two combustion models satisfactorily capture this trend for both fuels, and better agreement with the experiments is observed for the downstream locations. The axial and radial velocities increase away from the center and decrease with increasing spray cone angle. These trends are accurately captured for the near-nozzle regions as well as in the downstream regions for both fuels. Overall, the Lagrangian spray setup can accurately capture the spray breakup and evaporation.

Flame shape comparison
OH* chemiluminescence data from the UIUC experiments (Mayhew et al., 2017) were utilized to compare the line-of-sight average OH mass fraction from LES simulations for four kinetic mechanisms and two combustion models. The results for detailed, skeletal, reduced, and compact mechanisms are displayed in Figure 9 alongside the experimentally observed OH* chemiluminescence. The results from the detailed, skeletal, and reduced mechanisms are qualitatively similar, and the
experimental data (OH* chemiluminescence) and detailed mechanism calculations (OH) show similar spreads in the radial and axial directions. However, it must be noted that these comparisons are qualitative in nature. The experimental images are based on false color and do not indicate a quantitative measurement of the OH field. The horizontal position of 0 mm corresponds to the deflector plate. OH formation marks the high-temperature heat release region, which extends 50 mm downstream of the deflector plate and also corresponds to the downstream location of the first row of dilution holes. This area is the stable region of the swirl-stabilized flame and exhibits a truncated cone shape, with regions of high OH/heat release corresponding to the cone angle of the hollow spray cone. This trend indicates strong burning and heat release near the spray cone surface downstream of the swirl cup. The A2 fuel exhibits a higher degree of asymmetry in OH* for this configuration and measurement. These regions of intense heat release are qualitatively captured by all four chemistry mechanisms. The flame shape computed for the FGM combustion model shows a stronger and larger reaction zone compared with the FRC model.

LBO approach

![Image of LBO approach](image_url)

Figure 7. Staged fuel ramp-down approach for lean blowout (LBO) prediction. The red dot represents the measured LBO global equivalence ratio.
Figure 8. Comparison of spray statistics and phase Doppler anemometry (PDA) data (Mayhew et al., 2017) for a stable flame at $\phi = 0.096$. 
Figure 9. Line-of-sight average OH mass fraction obtained from LES compared with experimental OH* obtained from chemiluminescence.

The computed velocity, temperature, and mean OH mass fraction contours are compared for the FRC and FGM combustion models in Figure 10. The results for the FRC model show a pointed flame root and a smaller reaction zone, whereas the FGM model results show a stronger flame root and a much larger reaction zone. However, experimental validation data would be highly beneficial to verify the computational model results and to guide further enhancements in the model.

Figure 10. Comparison of temperature (filled contours), velocity (vectors), and an isocontour for a mean OH mass fraction of 5e-04 (black line) for C1 fuel.
**Heat release rate**
The evolutions of the heat release rate for varying equivalence ratios and for two fuels under the FGM combustion model are shown in Figure 11. The flame is initially stable; subsequently, a steady decrease followed by a sharp reduction in the heat release rate is observed for both the A2 and C1 fuels. The heat release rates are allowed to reach a steady state prior to the next step. In this figure, the dotted black line shows the mean heat release rate, and the dotted pink line shows the ideal heat release rate.

![Heat release rate under the flamelet-generated manifold (FGM) combustion model.](image)

**LBO equivalence ratio comparison**

![Comparison of lean blowout (LBO) equivalence ratios from experiments and LES, including results from detailed chemistry and the flamelet-generated manifold (FGM) combustion model.](image)
The LBO trends for both fuels are compared with experimental results in Figure 12. The C1 fuel blows out at a higher equivalence ratio compared to A2 in the experiments. This LBO dependence on the fuel’s physical and chemical properties is very complex. The simulations with the FRC and FGM combustion models can qualitatively capture the LBO trend and relative behaviors for each fuel. However, the FGM model predicts that LBO will occur at a lower equivalence ratio compared to the FRC model due to the stronger flame root and larger reaction zone, as shown in Figures 9 and 10.

Analysis of scalars in the primary zone
As shown in Figure 13, a control volume within the primary zone of the combustor was chosen for scalar analysis in an effort to understand the LBO mechanism and to identify the precursors for early detection of incipient LBO conditions. The volume-averaged equivalence ratio, temperature, and mass fractions of OH and CH$_2$O (HCHO) are shown in Figure 14. Under near-stable flame conditions, all variables decrease with time. During LBO, as the equivalence ratio decreases, the temperature and OH decrease, but the CH$_2$O concentration increases due to partial oxidation. A similar trend towards the onset of LBO has been observed experimentally at Cambridge for a swirl-stabilized laboratory combustor (Giusti & Mastorakos, 2017).

Figure 13. Sampling region within the primary zone for investigating the combustion process during lean blowout (LBO).
Domain sensitivity study

The previous LES simulations were performed with a reduced plenum size and excluded bypass air passages near the combustor exit. The air flow rate at the domain inlet was also reduced to account for these excluded bypass passages. However, it would be beneficial to clarify the effect of plenum size on the air flow splits and the resulting combustor flow field. During 2019, we initiated efforts to model the actual size of the plenum in the rig hardware and included all bypass air passages near the combustor exit. Computational modeling of the actual plenum size with all combustor passages has been completed, and these new simulations will be applied with the actual rig inlet air flow rate of 391.4 g/s at the computational domain inlet. The reduced and actual plenum domains are compared in Figure 15. A domain sensitivity study was performed under nonreacting conditions, and LES simulations were completed during the 4th quarter of 2019. These results will be analyzed during the 1st quarter of 2020. Reacting LES simulations and LBO computations will be performed based on the domain impact on the flow splits and combustor flow field.
Figure 15. Comparison of computational domains with the reduced (left) and actual plenum (right) size.

Publications

Peer-reviewed journal publications


Published conference proceedings


Hasti, V.R., Kumar, G., Liu, S., Lucht, R.P., & Gore, J.P. (2018). A computational study on H2 pilotd turbulent methane / air premixed flame with CO2 dilution. 2018 Spring Technical Meeting, Central States Section of the Combustion Institute, Minneapolis, MN 55455 USA


Outreach Efforts
N/A

Awards
- Veeraraghava Raju Hasti received the Gordon C. Oates Air Breathing Propulsion Graduate Award - 2019 from the AIAA Foundation. The AIAA Foundation presents this award to a graduate student performing excellent research in air and space science.
- Veeraraghava Raju Hasti received the Computational Interdisciplinary Graduate Program's Bilsland Dissertation Fellowship from Purdue University in 2019.
• Veeraraghava Raju Hasti received the Outstanding Graduate Student Mentor award from Purdue University in May 2019.
• Veeraraghava Raju Hasti received the Outstanding Service award from the College of Engineering, Purdue University in May 2019.
• Veeraraghava Raju Hasti won 1st prize (best poster) under the 100 Years Category in the Sustainable Economy and Planet Poster Competition for PhD Students, Ideas Festival, 150 Years Celebrations at Purdue University for his poster presentation entitled “Quantum Computers on Artificial Intelligence: Automatic and Adaptive Solutions,” given February 6, 2019.
• Veeraraghava Raju Hasti delivered an invited talk entitled “Computational methodology for biofuel performance assessment” at the Spring CIGP Symposium, Purdue University, April 17, 2019.
• Veeraraghava Raju Hasti was elected as Chair for the Membership Committee of the Gas Turbine Engines Technical Committee (GTE TC), AIAA, August 2019.
• Veeraraghava Raju Hasti delivered an invited talk entitled “Computational Methodology for Biofuel Performance Prediction” at the Academic Research Colloquium, University of Dayton, September 10–12, 2019.
• Veeraraghava Raju Hasti successfully defended his PhD dissertation on October 30, 2019.
• Veeraraghava Raju Hasti served as a Global Ambassador following selection by the Purdue Graduate School for interactions with prospective international students on November 8, 2019.
• Veeraraghava Raju Hasti represented Purdue University at the Big Ten Grad Expo on September 22, 2019, following selection by the Office of Interdisciplinary Graduate Programs and Computational Interdisciplinary Graduate Programs. Hasti also served on a Panel at the Big Ten Grad Expo on September 22, 2019.
• Veeraraghava Raju Hasti was invited by the College of Engineering to serve on the Graduate Students Panel on May 21, 2019 to interact with global undergraduate summer interns through the Purdue Undergraduate Research Experience (PURE).
• Veeraraghava Raju Hasti delivered a presentation on computational research opportunities in combustion and energy at the Mechanical Engineering Visitation Program for prospective graduate students on February 14, 2019 at Purdue University.

**Student Involvement**
PhD student Daniel Shin is primarily responsible for performing PDA measurements under LBO and HAR/GLO conditions and for upgrading the VAPS test rig in a new test cell. PhD student Neil Rodrigues and postdoctoral research associate Rohan Gejji assist with the project when their expertise is required. PhD student Veeraraghava Raju Hasti is primarily responsible for developing and performing the LES simulations. Veeraraghava Raju Hasti has graduated and is currently a Research Assistant Professor in the School of Mechanical Engineering at Purdue.

**Plans for Next Period**
The proposed deliverables and tasks for FY2020 are listed below.

**Year-5 deliverables**
The year-5 deliverables for Area 5, Project 29A are as follows:

**Experimental**
1. Complete the VAPS test rig integration and prepare the rig for operation
2. Begin PLIF measurements of A2 fuel under LBO and elevated ambient pressure conditions
3. Perform PDA measurements of C3 fuel under near-LBO conditions
4. Continue revisions and complete the spray section in the AIAA book chapter
5. Continue interactions with the three CFD groups (Ihme, Vaidya, and Menon)
Computational

1. Contribute to writing of the CFD book chapter
2. Complete the domain sensitivity analysis under nonreacting conditions
3. Perform reacting LES simulations with the partially stirred reactor (PaSR) combustion model and LBO computations for the actual plenum computational domain if the plenum size has a significant impact on the flow splits and combustor flow field
4. Compare results from completed FRC simulations, including any simulation results without zonal chemistry being applied during the simulation, using HyChem detailed, skeletal, and reduced mechanisms to determine why inaccurate trends are obtained for the detailed and reduced mechanisms
5. Analyze reaction pathways to identify the key chemical pathways responsible for LBO and compare these pathways for A2 and C1 fuels
6. Conduct new simulations based on tasks 9 and 10 to understand or improve consistency among the HyChem detailed, skeletal, and reduced mechanisms
7. Publish journal papers on computational efforts

The tasks to be performed for FY2020 are listed below:

Quarter 1 FY2020

1. Complete the upgraded VAPS test rig integration and prepare the rig for operation
2. Conduct PLIF measurements for the A2 fuel
3. Publish a manuscript describing the cold start measurements in the AIAA Journal
4. Continue work on the spray section of the AIAA book chapter
5. Share boundary, initial, and operating conditions and resulting experimental data with the correlations and modeling teams (Rizk, Ihme, Menon, and Sankaran)
6. Contribute to writing of the CFD book chapter
7. Complete the domain sensitivity analysis under nonreacting conditions

Quarter 2 FY2020

1. Collaborate with Area 4 and Area 6 members and with the spray subcommittee to develop an experimental test matrix for year 5
2. Conduct further PLIF measurements for the PhD thesis work of graduate student Daniel Shin
3. Share boundary, initial, and operating conditions and resulting experimental data with the correlations and modeling teams (Rizk, Ihme, Menon, and Sankaran)
4. Continue work on the CFD book chapter
5. Perform reacting LES simulations with the PaSR combustion model and LBO computations for the actual plenum computational domain if the plenum size has a significant impact on the flow splits and combustor flow field
6. Compare results from completed FRC simulations, including any simulation results without zonal chemistry being applied during the simulation, using the HyChem detailed, skeletal, and reduced mechanisms to determine why inaccurate trends are produced for the detailed and reduced mechanisms

Quarter 3 FY2020

1. Prepare a journal paper on the elevated ambient pressure measurements
2. Share boundary, initial, and operating conditions and resulting experimental data with the correlations and modeling teams (Rizk, Ihme, Menon, and Sankaran)
3. Continue work on the CFD book chapter
4. Analyze reaction pathways to identify the key chemical pathways responsible for LBO and compare these pathways for A2 and C1 fuels
5. Prepare journal manuscripts based on the reaction pathway analysis

Quarter 4 FY2020

1. Share boundary, initial, and operating conditions and resulting experimental data with the correlations and modeling teams (Rizk, Ihme, Menon, and Sankaran)
2. Conduct new simulations if required to understand or improve consistency among the HyChem detailed, skeletal, and reduced mechanisms
References